

Scanning the quark-gluon plasma with charmonium

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We suggest the variation of charmonium production rate with Feynman x_F in heavy ion collisions as a novel and sensitive probe for the properties of the matter created in such reactions. In contrast to the proton-nucleus case where nuclear suppression is weakest at small x_F , final state interactions with the comoving matter create a minimum at $x_F = 0$, which is especially deep and narrow if a quark-gluon plasma is formed. While a particularly strong effect is predicted at SPS, at the higher RHIC energy it overlaps with the expected sharp variation with x_F of nuclear effects and needs comparison with proton-nucleus data. If thermal enhancement of J/Ψ production takes over at the energies of RHIC and LHC, it will form an easily identified peak, rather than dip in x_F dependence. We predict a steep dependence on centrality and suggest that this new probe is complementary to the dependence on transverse energy, and is more sensitive to a scenario of final state interactions.

Although modification of the charmonium (Ψ) production rate due to final state interactions (FSI) with the matter created in relativistic heavy ion collisions may serve as a probe for its properties [1], it is still a challenging problem how to disentangle the nuclear suppression at the early stage of a collision, when the nuclei propagate through each other, from the late stage FSI, when charmonium with a low speed travels through the comoving debris of the nuclei. Since the former seems to be so far the main source of suppression, uncertainties which exist in understanding the early stage nuclear effects are transferred to the interpretation of FSI.

Even the very manifestation in the data of final state suppression is still disputed. Although the dependence of charmonium suppression on impact parameter (E_T dependence) cannot be reproduced by the simplest model, where the effect is related only to absorption in cold nuclear matter [2], a deeper insight into the dynamics of nuclear collisions discovers more sophisticated nuclear effects [3, 4, 5] which might nearly explain the observed E_T dependence. Currently, only the falling E_T dependence of suppression for most central collisions perhaps signals about the presence of late stage interactions, since it is apparently related to fluctuations of the density of produced matter [6, 7, 8, 9]. However, even in this case it is still difficult to discriminate between the models of comoving hadrons [6] and phase transition to the quark gluon plasma [7].

In this letter we suggest a new sensitive probe for interaction of charmonium with the produced matter and possibly to discriminate between the models [6, 7]. This is the dependence on Feynman x_F of the ratio $R_{AB}(x_F)$ of charmonium production rates in nucleus-nucleus and pp collisions, which is expected to expose a deep minimum at small x_F due to absorption effects in the final state. On the other hand, the early stage of interaction with the nuclei leads to a maximum at small x_F . The

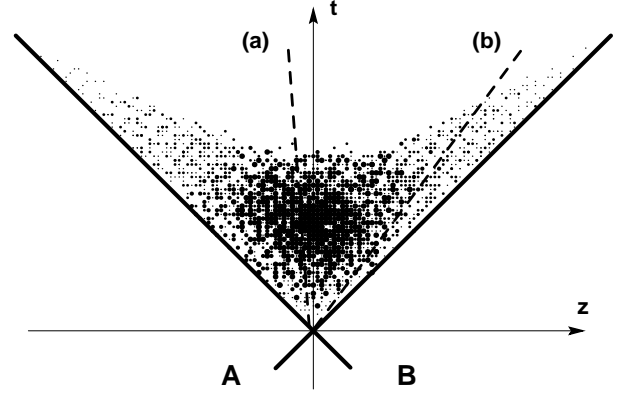


FIG. 1: Development of a nucleus-nucleus collision as function of longitudinal coordinate z and time t in the c.m. frame. Dashed lines show trajectories of charmonia produced with small (a) and large (b) values of x_F .

shape of the minimum turns out to be sensitive to the properties of the produced matter, it is deeper and narrower if a phase transition to a deconfined quark-gluon plasma takes place. On the contrary, if thermal enhancement [10, 11, 12] of J/Ψ production takes over in the energy range of RHIC and LHC, it will create a peak in the $R_{AB}(x_F)$ at $x_F = 0$ which should be clearly identified comparing with pA data.

The production time of quarks and gluons $\sim 1/k_T$ correlates with their transverse momenta and is usually longer than the one of a charmonium $\sim 1/m_\Psi$. Therefore, interaction of the charmonium with a comoving quark-gluon or hadronic gas factorizes from the early stage of production and interaction with the nuclei. Depending on the value of x_F , charmonium travels through different regions of the produced matter, which is more dense at mid rapidity ($x_F = 0$) while it becomes more dilute with rising x_F . This is indicated in Fig. 1, where different trajectories are shown by dashed lines. Thus, the char-

monium scans the produced matter at different rapidities depending on its value of x_F . Apparently, the survival probability of a charmonium propagating at $x_F = 0$ through the most dense medium is minimal, *i.e.* final state attenuation should create a dip at $x_F = 0$. The shape of this minimum depends on the properties of the comoving matter and we give two model examples which employ the ideas of either comoving hadrons [6] or phase transition [7].

Coming to the details of our calculation, we write the differential cross section for Ψ production in nucleus-nucleus (AB) collisions, as function of x_F and impact parameter \mathbf{b} , as

$$\frac{d^3\sigma_{AB}^{\Psi}}{d^2\mathbf{b}dx_F} = \frac{d\sigma_{NN}^{\Psi}}{dx_F} \int d^2\mathbf{s} T_A(\mathbf{s}) T_B(\mathbf{b} - \mathbf{s}) \times S_{NUC}(\mathbf{b}, \mathbf{s}, x_F) S_{FSI}(\mathbf{b}, \mathbf{s}, x_F), \quad (1)$$

where T_A and T_B are the nuclear thickness functions, while S_{NUC} and S_{FSI} represent the modification factors due to nuclear effects and FSI with the produced medium, respectively.

We now examine the features of nuclear suppression S_{NUC} in AB collisions, setting for the moment $S_{FSI} = 1$. To perform calculations we employ the approximation of factorization

$$S_{NUC}(\mathbf{b}, \mathbf{s}, x_F) = S_{pA}(\mathbf{s}, x_F) S_{pB}(\mathbf{b} - \mathbf{s}, -x_F), \quad (2)$$

which is accurate within the dynamics discussed below. The observed x_F dependence of the suppression factor $S_{pA}(\mathbf{s}, x_F)$ at the energies of SPS [13, 14] is well understood in terms of absorption, energy loss [15, 16] and formation time effects [17, 18]. Therefore, we can use model predictions for $S_{pA}(\mathbf{s}, x_F)$. The agreement with the data is very satisfactory and allows a reliable baseline calculation for the AB case [19].

Nuclear suppression as function of x_F at given impact parameter \mathbf{b} of AB collision is given by the ratio,

$$R_{AB}(x_F, \mathbf{b}) = \frac{1}{T_{AB}(\mathbf{b})} \frac{d\sigma_{AB}^{\Psi}/d^2\mathbf{b}dx_F(x_F, \mathbf{b})}{d\sigma_{pp}^{\Psi}/dx_F(x_F)}. \quad (3)$$

Averaging with the thickness function T_{AB} , we also compute the ratio of total cross section in AB collisions with respect to the pp case, *i.e.*

$$R_{AB}^{tot}(x_F) = \frac{1}{AB} \int d^2\mathbf{b} T_{AB}(\mathbf{b}) R_{AB}(x_F, \mathbf{b}). \quad (4)$$

These ratios for PbPb collisions at $E_{lab} = 158$ GeV integrated over \mathbf{b} and at $\mathbf{b} = 0$ are plotted with dotted curves labeled “*NUC*” in Fig. 2 in large and small panels, respectively. One can notice an approximately flat behavior for $|x_F| \leq 0.3$ and a rapid fall off at large x_F .

The mechanism of nuclear suppression completely changes at the high energies of RHIC. Energy loss effects vanish, but coherence effects come into play [20]. The

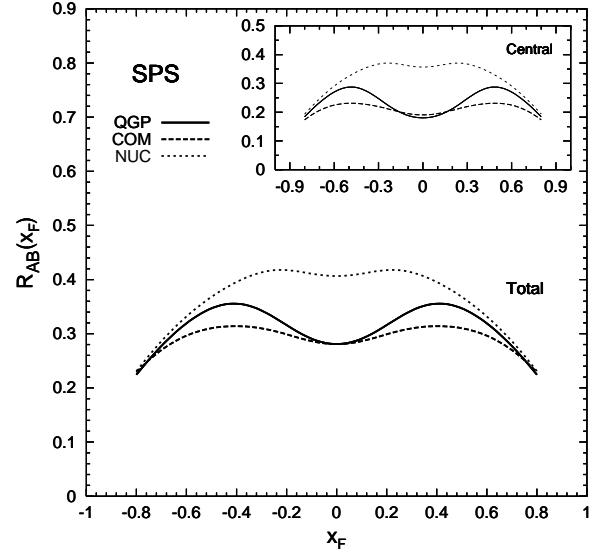


FIG. 2: Ratios of cross sections of charmonium production as function of x_F for PbPb collisions at SPS, with respect to the pp case. The dotted curve presents the effect of nuclear suppression alone. Dashed and full lines refer to the full suppression resulting from nuclear effects and also from interaction with plasma or comovers, respectively. The large and small panels represent the results for total cross section and central collisions, respectively.

conventional probabilistic treatment of production and absorption of the $c\bar{c}$ pair becomes incorrect, since amplitudes at different space-time points become coherent and interfere. This leads to additional suppression which is an analog to shadowing of c -quarks in DIS. Moreover, gluon shadowing becomes the main source of suppression of Ψ production. While these coherence effects barely exist at SPS, their onset has been already observed at Fermilab [21] where they lead to a nuclear suppression at large x_F approximately as strong as at the SPS energies, in spite of a substantial reduction of the energy loss effects. Since the parameter free calculation of the coherence effects performed in [20] are in a good accord with the Fermilab data [21], we can rely on it in order to predict the nuclear suppression factor using eq. (2) for AuAu collision at $\sqrt{s} = 200$ GeV, shown by dotted curves in the two panels of Fig. 3. One can see a new feature, absent in the SPS case. The strong coherence effects, mostly gluon shadowing, form a rather narrow peak in the x_F dependence of nuclear suppression.

Unfortunately, predictions for S_{FSI} in (1) are still ambiguous, whatever properties of the produced matter are assumed. Nevertheless, to examine the scale of the expected effect in the x_F distribution, we consider two popular scenarios of FSI. As we will see, the shape of x_F distribution turns out to be quite sensitive to the distinction between the models.

The first model [6] assumes that the medium is com-

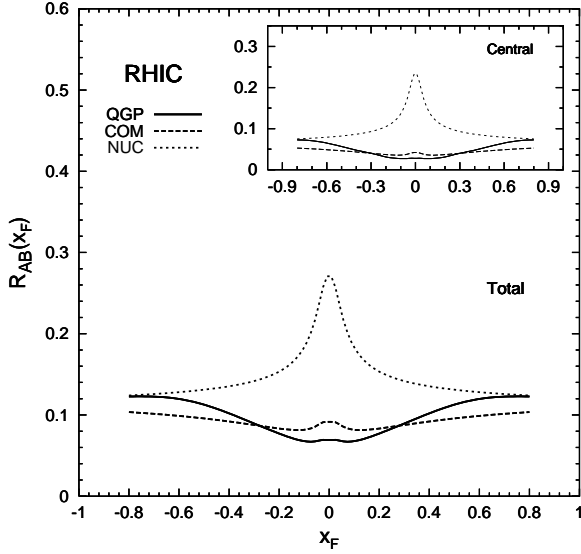


FIG. 3: The same as in Fig. 2, but for gold-gold collisions at RHIC energy $\sqrt{s} = 200 \text{ GeV}$.

posed by comoving hadrons and provides the suppression factor

$$S_{FSI}^{COM}(\mathbf{b}, \mathbf{s}) = \exp \left[-\sigma_{co} n_{co}(\mathbf{b}, \mathbf{s}) \ln \left(\frac{n_{co}(\mathbf{b}, \mathbf{s})}{n_{fo}} \right) \right], \quad (5)$$

where $n_{co}(\mathbf{b}, \mathbf{s})$ is the comover density in impact parameter plane, the freeze-out density $n_{fo} = 1.15 \text{ fm}^{-2}$ and $\sigma_{co} = 1 \text{ mb}$ are fitted parameters. In this model, the absorption cross section controlling the factor $S_{NUC}(\mathbf{b}, \mathbf{s}, x_F)$ in (1) is adjusted at $\sigma_{\Psi N}^{abs} = 4.5 \text{ mb}$.

The scenario of ref. [7] considers the possibility of QGP formation and assumes that charmonium is not absorbed at all unless the latter experiences a phase transition, which occurs when the transverse density of participants $n_p(\mathbf{b}, \mathbf{s})$ is close to the critical value n_{cr} , yielding the suppression factor

$$S_{FSI}^{QGP}(\mathbf{b}, \mathbf{s}) = \frac{1 + \tanh\{\lambda [n_{cr} - n_p(\mathbf{b}, \mathbf{s})]\}}{2}. \quad (6)$$

Here $n_{cr} = 3.4 \text{ fm}^{-2}$ and the smearing factor $\lambda = 2 \text{ fm}^2$ are fitted parameters. In this model the nuclear absorption cross section is adjusted to $\sigma_{\Psi N}^{abs} = 6.4 \text{ mb}$ and is larger than in the comover model.

Both models are fitted to describe the observed E_T dependence of suppression at the mean value $\bar{x}_F = 0.15$ of the NA50 experiment. In order to incorporate an x_F dependence into these models one must admit that the density and properties of the produced matter which is scanned by charmonium as is illustrated in Fig. 1, varies with rapidity or x_F . Ψ s with small values of x_F cross the medium in its most dense part, while if their values of x_F are large, they interact only with a dilute matter. We assume that the rapidity distributions of the produced

matter traversed by Ψ and of the observed hadrons are proportional. Therefore, we re-scale the densities of comovers n_{co} in (5) and of participants in (6) as

$$n(\mathbf{b}, \mathbf{s}) \Rightarrow n(x_F, \mathbf{b}, \mathbf{s}) = r(x_F) n(\mathbf{b}, \mathbf{s}), \quad (7)$$

where the x_F -dependence is introduced by the factor

$$r(x_F) = \frac{dN^h/dy}{dN_{SPS}^h/dy(x_F = 0.15)}, \quad (8)$$

which is assumed to be independent of impact parameter of collision. This approximation is supported by data from the SPS [22] and RHIC [23]. The rapidity y of the comoving matter is the same as that of charmonium. The latter is related to the x_F of Ψ as $y(x_F) = (1/2) \log(x_1/x_2)$. Here $x_{1,2} = k_{\Psi}^{\pm}/k_N^{\pm}$ are the fractions of light-cone momenta of the colliding nucleons carried by Ψ . The normalization $r(x_F = 0.15) = 1$ at SPS guarantees that the models under discussion are unmodified for the kinematics of the NA50 experiment.

Note that the number of participants in eq. (7) is not meant to depend on x_F . In fact, a phase transition in the plasma model should be a function of the produced energy, which is assumed in eq. (6) to be proportional to the number of participants with a coefficient dependent on x_F . This x_F dependence is effectively implemented in eq. (7).

We parametrize the rapidity density as the sum of two Gaussians

$$\frac{dN^h}{dy}(y) = N \frac{\exp(-y_{\pm}^2/\Delta^2) + \exp(-y_{\pm}^2/\Delta^2)}{2 \exp(-Y^2/\Delta^2)}, \quad (9)$$

symmetrically shifted from mid-rapidity by the amount Y , appearing in $y_{\pm} = y \pm Y$, and characterized by a width Δ . The rapidity density is normalized to N at mid-rapidity. The set of parameters N , Y and Δ is compared to SPS and RHIC measurements of hadron spectra. For SPS we take the negative hadrons rapidity distribution in central events [22] and are able to reproduce it with $\Delta_{SPS} = 1.5$ and $Y_{SPS} = 0.75$. We scale it up by a factor 3 to the total number of hadrons, which is about $N_{SPS} = 600$ at mid-rapidity, considering that most of the hadrons are pions. For RHIC we first take the charged hadrons pseudo-rapidity (η) distribution, measured at $\sqrt{s} = 130 \text{ GeV}$ [23], also for central events, and convert it to the one in rapidity with the transformation

$$d/d\eta = \left[1 + (m/p_{\perp} \cosh \eta)^2 \right]^{-1/2} d/dy, \quad (10)$$

assuming an average mass $m = 200 \text{ MeV}$ for the hadrons and a mean value of the transverse momentum $p_{\perp} = 0.5 \text{ GeV}$. We then scale it up by a factor $3/2$ to get the total number of hadrons, and by a factor $(200/130)^{0.36}$, to extrapolate to $\sqrt{s} = 200 \text{ GeV}$. The power energy dependence, s^{δ} , of the inclusive cross section is dictated

by the AGK cutting rules [24], and we fixed $\delta = 0.18$ interpolating between the measurements at 56 and 130 GeV. This is close to $\delta = 0.17$ found from data on inclusive pion production in pp collisions [25]. Neglecting for simplicity that the width of the rapidity distribution also depends on the collision energy, we obtain the values $\Delta_{RHIC} = 2.4$ and $Y_{RHIC} = 1.75$, with a normalization $N_{RHIC} = 1000$.

The results for SPS are shown in Fig. 2. The curves correspond to nuclear effects only (dotted), model of comovers (dashed) labeled “COM”, and to the plasma model (full) labeled “QGP”, respectively. The “COM” and “QGP” models include nuclear suppression as it is calculated in [6, 7]. The big and small panels show $R_{AB}^{tot}(x_F)$ and $R_{AB}(x_F, \mathbf{b} = 0)$, respectively. One clearly observes that the plasma model leads to a more pronounced dip, while the comover model produces only a slight depression. This feature is due to FSI with the created medium and reflects its properties.

The predictions for RHIC are depicted in Fig. 3. Nuclear effects form a rather narrow peak (dotted curve) in $R_{AB}(x_F)$. Applying calculated with [6, 7] FSI suppression, which at RHIC is a very narrow dip which extends over about the same range in x_F as the peak caused by nuclear effects, one ends up with a rather flat x_F dependence. Note that the small irregularity around of $x_F = 0$ is an artifact of the used parameterizations and is within the theoretical uncertainty. Since the FSI effect can be well singled out comparing with pA collisions, we emphasize the necessity of pA measurements. Indeed, we do not expect a dramatic variation of the shape with impact parameter since no peak is expected for peripheral collisions.

Concluding, we suggest a novel probe for the matter created in heavy ion collisions which is scanned by a charmonium produced with different x_F . At SPS, we predict a pronounced minimum of survival probability at $x_F = 0$ which can occur uniquely by interaction of Ψ with the QGP. Its properties define the shape and depth of the minimum, which varies with impact parameter, it is maximal for central collisions and disappears for peripheral ones. In the comover case the survival probability turns out to be rather flat. At the energies of RHIC coherence effects form a narrow peak at $x_F = 0$, whose height is substantially reduced due to the two different medium effects considered. Although it will be difficult to distinguish the two FSI scenarios, the prediction is rather interesting and can be confirmed after comparing to pA data taken at the same energy.

A possibility of FSI enhancement of Ψ , rather than suppression, due to fusion of produced $c\bar{c}$ s has been recently suggested [10, 11, 12] to be present at RHIC. In this case FSI would enhance the maximum produced by the nuclear factor S_{NUC} in (1) leading to a dramatic effect easily observable. However, while gluon shadowing leads to a very strong suppression of direct Ψ s it should

diminish even more (by square of that) the fusion mechanism. This interesting problem needs further study.

Note that similar scanning is also possible with other hard processes, for example jet quenching [26]. One should measure di-jets or di-hadrons in back-to-back geometry, *i.e.* with $\vec{p}_T^1 = -\vec{p}_T^2$ and $x_F^1 = -x_F^2$. The energy loss effect in a plasma is expected to have a similar x_F dependence, *i.e.* to provide stronger quenching at $x_F = 0$.

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